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13 October 2016

Version of attached file:

Accepted Version

Peer-review status of attached file:

Peer-reviewed

Citation for published item:

Yang, Zhutian and Ping, Shuyu and Sun, Hongjian and Aghvami, A. Hamid (2016) 'CRB-RPL : a receiver-based routing protocol for communications in cognitive radio enabled smart grid.', *IEEE transactions on vehicular technology*, 66 (7). pp. 5985-5994.

Further information on publisher's website:

<https://doi.org/10.1109/TVT.2016.2617874>

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CRB-RPL: A Receiver-based Routing Protocol for Communications in Cognitive Radio Enabled Smart Grid

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Abstract—As a tool of overcoming radio spectrum shortages in wireless communications, cognitive radio technology plays a vital role in future smart grid applications, particularly in Advanced Metering Infrastructure (AMI) networks with Quality of Service (QoS) requirements. This paper focuses on the investigation of the receiver-based routing protocol for enhancing QoS in cognitive radio-enabled AMI networks, due to their potentials of enhancing reliability and routing efficiency. In accordance with practical requirements of smart grid applications, a new routing protocol with two purposes is proposed: one is to address the realtime requirement while another protocol focuses on how to meet energy efficiency requirements. As a special feature of cognitive radio technology, the protocol have the mechanism of protecting primary (licensed) users whilst meeting the utility requirements of secondary (cognitive radio) users. System-level evaluation shows that the proposed routing protocol can achieve better performances compared with existing routing protocols for cognitive radio-enabled AMI networks.

Index Terms—Smart grid, Cognitive radio, AMI network, Receiver-based routing, Hop energy efficiency.

I. INTRODUCTION

THE legacy electric power grids are facing numerous challenges, such as ageing infrastructure, energy inefficiency, frequent transmission congestions and even failures [1]–[3]. The next generation of electric grids, termed as *smart grids*, are expected to supply improved service with higher reliability, efficiency, agility and security [4]–[6], due to their capabilities of advanced bi-directional communications, automated control and distributed computing. Electricity providers, distributors, and consumers would benefit realtime awareness of operating environments, requirements and capabilities since smart grids are capable of gathering information from equipment in realtime from different areas and then making intelligent decisions to promote energy efficiency and security of electric grids [7], [8].

One key element of smart grids is *Advanced Metering Infrastructure* (AMI), which consists of multiple smart me-

ters communicating with Meter Data Management Systems (MDMS). The AMI networks are essential in smart grids, since they provide two-way communications between utilities and consumers. They provide not only periodic energy measurements, but also real-time information, such as demand response and fault detection, so that utilities can keep track of consumers' electricity usage, monitor power quality, and inform consumers the latest electricity prices on a realtime basis.

Therefore, low-latency and high reliability are essential for AMI applications [9]. In addition, energy crisis is an emerging problem all over the world. As a result, energy efficiency is a critical issue for AMI networks, especially for battery-powered AMI network communications, which may pose new practical issues when AMI networks are massively deployed for smart grids. To our best knowledge, the energy efficiency of AMI networks is efficiently covered. On the other hand, *Cognitive Radio* (CR) [10]–[14] is considered as an effective tool to address the spectrum scarcity and spectrum inefficiency issues in wireless communications. It also plays an important role in mitigating interference and improving energy efficiency for future communication networks [15]. Therefore, CR technologies would be very helpful for smart grid communications [12], [16]. Recently, a number of studies have been presented, such as literatures [10], [11], [17]–[20], where Routing Protocol for Low Power and Lossy Networks (RPL) are of primary focus. However, in these protocols, one has to calculate the next hop for routing and suit to a mesh network topology due to the *sender-based* nature. In addition, default receivers may be invalid due to the randomness of CR networks, which will lead to more retransmissions and lower routing efficiency and energy efficiency.

Against this background, this paper aims to propose a new RPL-based routing protocol for CR-enabled AMI networks with improved routing efficiency and energy efficiency. The proposed routing protocol, termed as CRB-RPL (Cognitive Receiver-based RPL), is receiver-based, and supplies two classes of routing for meeting two important smart grid requirements, i.e., latency (delay) and energy efficiency. Some distinct features of this paper are outlined below:

- An efficient routing protocol is proposed to improve realtime performance and energy efficiency of cognitive AMI networks in smart grids, which consist of two classes of routing, i.e., class *A* and class *B*. The former one is for realtime smart grid applications with low latency

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The research leading to these results has received funding from the European Commission's Horizon 2020 Framework Programme (H2020/2014-2020) under grant agreement No. 646470, SmarterEMC2 Project.

requirements, whereas the latter one is designed for green smart grid applications where the energy efficiency is of primary interest.

- The receiver-based mechanism is utilized for designing the routing, resulting in higher *Link Success Probability* (LSP) than those of sender-based approaches. The sender does not assign a particular receiver node. All neighboring nodes can receive the packet. Therefore, the receiver-based routing can take advantage of broadcasting nature of wireless communications to reduce retransmissions, thus leading to higher routing efficiency.
- The concept of *Cognitive Transmission Quality* (CTQ) is first termed in this paper, which is used to describe the tradeoff between the transmission quality and the interference to PU receivers in CR networks. CTQ is then used to compute the ranks of nodes such that the requirements of both QoS of the CR network and protection of PU receivers are balanced.
- The concept of *Hop Energy Efficiency* (HEE) is proposed for quantifying the energy efficiency of a single hop operation, such that the energy efficiency of transmission on virtual distance in multi-hop networks can be quantitatively described.
- A response-based election mechanism is adopted for next-hop node competition in routing, wherein the node making response first will be the winner. Before making response, nodes must wait for a duration, whose length is decided on the receiver's rank or HEE. In class A, the receiver's rank is the key factor for response speed, such that the receiver node nearer to gateway has larger opportunity to forward the packet. In class B, the HEE is the key factor, in order to improve the energy efficiency of the whole AMI network.

The rest of this paper is organized as follows. Section II presents a literature review of RPL-based routing protocols for CR-enabled AMI networks. Section III presents the CRB-RPL framework, followed by the analytical modeling in Section IV. The routing protocol is then evaluated in Section V. Finally the paper is concluded in Section VI.

II. LITERATURE REVIEW OF RPL ROUTING PROTOCOL FOR CR-ENABLED AMI NETWORKS

RPL [21] is a routing protocol standardized by Internet Engineering Task Force to support a variety of applications including CR-enabled AMI networks [20]. In RPL, *Directed Acyclic Graphs* (DAGs) is used to maintain the network. Each client node in the DAG is assigned a rank to show its virtual position. The gateway (root node) has the lowest rank and the rank monotonically increases in the downward direction. A client node can only communicate with other nodes with same or smaller rank in order to avoid cycles. The gateway broadcasts a control message periodically to construct the DAG, which is called *DAG Information Object* (DIO). In the DIO, relevant network information is included, such as DAG ID rank information, and objective function.

When being used in CR networks, RPL needs modifications for protecting PU activities by using spectrum sensing techniques [22], [23]. Client nodes have to monitor the current

band periodically to check PU activities before occupying it for data transmission. This protection shall include both PU transmitters and PU receivers [24]–[26]. PU receivers are particularly important for those applications with unidirectional transmission, such as TV broadcast. However, PU receivers are difficult to be detected but easily affected by neighboring CR's transmissions. Therefore, any routing protocols should provide explicit protection to PU receivers by avoiding regions where such PUs might be present, although this may result in a performance degradation for CR networks. For more information about RPL, the interested reader is referred to our recent work [20].

III. CRB-RPL FRAMEWORK

A. General Description

In this section, the framework of CRB-RPL protocol is described particularly for CR-enabled AMI networks. This routing protocol is inherently *receiver-based*. Unlike *sender-based* protocol such as CORPL [20], where the sender selects a receiver node from its forwarder table, using CRB-RPL, a sender node broadcasts its packets without defining a particular node as the receiver. All the neighboring nodes within the communication range of the sender node could receive the data packet. Based on the rank information of sender, each receiver node decides if it is eligible to participate in forwarding. The receivers compete to be next hop node, and a response-based election is utilized for the next-hop competition.

Two classes of routing are supplied in CRB-RPL. For class A, the rank of the receiver is the key factor in the next hop competition. Receivers with lower ranks are more likely to forward packets, which can decrease the number of hops and end-to-end delay. Therefore, It is suitable to delay sensitive packets. For class B, the HEE is the key consideration. By selecting the receiver with best HEE for forwarding in each hop, class B improves the energy efficiency of routing for AMI networks.

Another key aspect of CRB-RPL is utilization of *preamble sampling*. In the preamble sampling approach, each node uses asynchronous low power listening and select the sleep/wakeup schedules independently. The nodes spend most of their time in sleep mode and wake up for a short duration, i.e., *Clear Channel Assessment* (CCA) in every Checking Interval (CI) to check whether there is an ongoing transmission. To avoid missed detections, the sender node transmits a long preamble as long as CI, before the data packet, to ensure that the preamble can be detected. Moreover, rank information of the sender is attached in the preamble such that receivers can make sure that they only receive the data from nodes with higher ranks.

B. System Model

In this paper, the static multi-hop wireless AMI network is considered, which consists of different smart meters (nodes) and a meter concentrator (gateway node). It is assumed that the smart meters are CR enabled. Each smart meter is equipped with a single radio transceiver, which can be tuned to any channel in the licensed spectrum.

We also assume that J stationary PU transmitters with known locations and maximum coverage ranges. The activity of PU transmitter can be described by a two-state independent distributed random process, i.e., $S^j, j \in [1, J]$. Let S_{busy}^j denote the state that the PU is active in j^{th} channel (busy state) with the probability $P_{busy}^j = \Pr(S^j = S_{busy}^j)$, while letting S_{idle}^j denote the state that no PU occupies the j^{th} channel (idle state) with the probability $P_{idle}^j = \Pr(S^j = S_{idle}^j)$, such that $P_{idle}^j + P_{busy}^j = 1$. Assuming that the duration of busy and idle periods are exponentially distributed with means of $\frac{1}{\mu_{ON}^j}$ and $\frac{1}{\mu_{OFF}^j}$, respectively, the probability of S_{busy}^j can be given by

$$P_{busy}^j = \frac{\mu_{OFF}^j}{\mu_{ON}^j + \mu_{OFF}^j}. \quad (1)$$

Each node employs energy detection technique for sensing primary signals, in which case the received energy (E) is compared with a predefined threshold (σ) to decide the state of j^{th} channel:

$$S^j = \begin{cases} S_{busy}^j & \text{if } E \geq \sigma \\ S_{idle}^j & \text{if } E < \sigma \end{cases}. \quad (2)$$

The probabilities of detection (P_d) and false alarm (P_f) for the j^{th} channel are given by

$$P_f^j = \Pr\{E \geq \sigma | S_{idle}^j\} = Q\left(\frac{\sigma - 2n_j}{\sqrt{4n_j}}\right), \quad (3)$$

$$P_d^j = \Pr\{E \geq \sigma | S_{idle}^j\} = Q\left(\frac{\sigma - 2n_j(\gamma_j + 1)}{\sqrt{4n_j(2\gamma_j + 1)}}\right), \quad (4)$$

where $Q(\cdot)$, γ_j and n_j denote Q function, the signal-to-noise ratio (SNR) of the primary signal and the bandwidth-time product for the j^{th} channel, respectively.

Let P_{sw}^j denote the probability of switching transmission to the j^{th} cognitive channel for a node (e.g., node i), P_{sw}^j can be evaluated considering two cases: (i) when S_{busy}^j , the node misses detecting it; (ii) when S_{idle}^j , no false alarm is generated. Therefore, P_{sw}^j is given by

$$P_{sw}^j = P_{busy}^j (1 - P_d^j) + P_{idle}^j (1 - P_f^j). \quad (5)$$

On MAC layer, a MAC frame structure in CR-AMI networks is made up of two slots, i.e., spectrum sensing slot (T_s) and transmission slot (T_t), which is shown in Fig. 1. In spectrum sensing slots, the CR nodes check the PU activity status of each channel, in order to find an available channel for transmission. In transmission slots, CR nodes access the selected channel, and perform data packet transmissions. Due to imperfect spectrum sensing in realistic conditions, there is a possibility of causing harmful interference to PUs in periodic spectrum sensing scenarios, which is quantified by *Interference Ratio* (IR). This paper assumes that the nodes employ optimal transmission time that maximizes the throughput of the secondary network subject to an interference constraint i.e., $IR_j \leq IR_{max}^j$, where IR_{max}^j denotes the maximum tolerable interference ratio on the j^{th} channel.

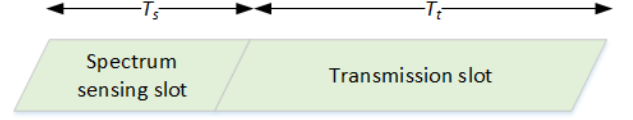


Fig. 1. Structure of a MAC frame in CR-AMI networks. A MAC frame consists of a spectrum sensing slot and a data transmission slot.

C. Protocol Description

In CRB-RPL, the DIO message is used to structure the dynamic DAG. After detecting a vacant channel, the gateway node transmits DIO messages periodically to identify client nodes and update node ranks. According to the CR environment, the Cognitive Transmission Quality (CTQ) is proposed to describe the tradeoff between QoS and protections to PUs for Cognitive Radio networks, which is defined by

Definition III.1. Cognitive Transmission Quality: In CR-enabled networks, the probability of the node b receiving a transmission from node a is termed as ρ_{ab} . The compossible ratio of transmission range area of node a with all PU transmitters is ε_a . The reciprocal of the weighted sum of ρ and ε_a is called Cognitive Transmission Quality (CTQ).

The CTQ of a link from node a to node b in a CR network can be given by

$$C_{ab} = \frac{1}{\omega_1 \cdot \rho_{ab} + \omega_2 \cdot (1 - \varepsilon_a)}, \quad (6)$$

where ω_1 and ω_2 are constants, ρ_{ab} is the probability of node a receiving a transmission from node b , and $\varepsilon_a = \sum_{j=1}^N c_{aj}$ denotes the net overlapping area of node a with all PU transmitters. The fractional area of node a transmission coverage under the coverage of j^{th} PU transmitter (i.e., c_{aj}) is given by (7), where R_j and r_a denote the coverage radii of the j^{th} PU transmitter and the node a respectively, and d_{aj} is the distance between j^{th} PU transmitter and node a .

Moreover, in order to reduce interference to PU receivers (which can be present anywhere in the coverage area of PU transmitters), the routes for the secondary network should be selected such that they pass through regions of minimum coverage overlap with the PU transmission coverage [20].

Therefore, the rank of node a is given by

$$Rank_a = \min\{Rank_p + \omega_3 \cdot C_{ap}\}, \quad (8)$$

where ω_3 is a constant; $p \in \mathbf{P}$, \mathbf{P} denotes the parent node set of node a . The rank computation method for a node joining the DAG is illustrated in Fig. 3.

Due to receiver-based mechanism [27], in CRB-RPL, the sender node does not select the receiver node for transmission. Instead, the sender broadcasts the preamble and data packet towards all its hop neighbors (within the transmission range). It is the receiver nodes that decide the next hop node. Specifically, the source node performs spectrum sensing (with duration given by T_s) to detect any PU activity firstly. If the channel is detected as busy with PU transmission, namely, S_{busy}^j , the sender node goes to sleep mode and waits for an available channel. The spectrum sensing operation is repeated after a

$$c_{aj} = \frac{1}{\pi} \cos^{-1} \left(\frac{1}{2d_{aj}r_a} \right) + \frac{R_j^2}{\pi r_a^2} \cdot \cos^{-1} \left(\frac{d_{aj}^2 + R_j^2 - r_a^2}{2d_{aj}R_j} \right) - \frac{1}{2\pi r_a^2} \sqrt{\{(R_j + r_a)^2 - d_{aj}^2\} (d_{aj} + r_a - R_j) (d_{aj} - r_k + R_j)} \quad (7)$$

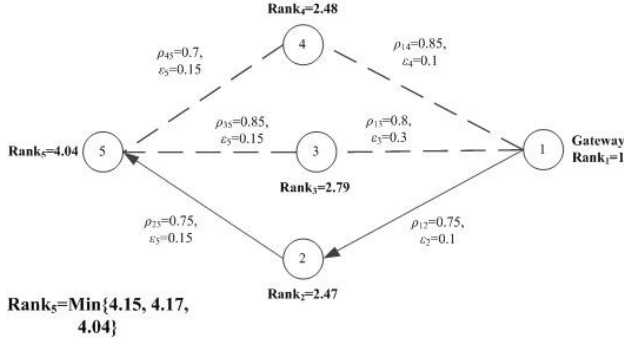


Fig. 2. Rank computation based on CTQ. The rank of a node is depended on link quality and fractional area between client nodes and PU transmitters. The lowest rank computed based on different parent nodes is adopted.

duration of checking interval (T_C). If the PU is detected to be absent, namely, S_{idle}^j , it starts transmitting the preamble followed by the data. The preamble, which last for T_{pr} , consists of multiple micro-frames, and each of micro-frame lasts T_m . The micro-frames carry necessary information for data packet identification, such as sequence number of the data, the sender's rank and data class.

All the nodes within the transmission range of the sender node will detect a few micro-frames of the preamble and extract necessary information. It is noted that nodes can only receive the packets from nodes with higher ranks. If the sender has a lower rank, the receiver will discard receiving data. Therefore, it is ensured that packets are transmitted towards the gateway node, which has the lowest rank in the network. The timeline of a single hop operation in CRB-RPL is shown in Fig. 3.

In Fig. 3, three neighboring nodes of S (i.e., nodes A , B , and C) are eligible to forward the data towards gateway. They wake up and receive the data transmitted from node S . If the received data packet is detected to be erroneous, it will be simply discarded. Otherwise, receivers will compete for forwarding the data packet, where a response-based election is adopted. Each node sets a timer Δt before forwarding the packet. The calculations of Δt is dependent on the delay sensibility of data and will be introduced in detail later. After Δt , the receiver node will restart spectrum sensing. If no channel is available, the node goes back to sleep mode for a duration T_C . When the node gets a free channel, it transmits the preamble followed by the data packet (e.g., node C in Fig. 3).

Moreover, when a node's transmission is found, each other node checks the sequence number. If the sequence number matches with its own, which means that the same packet has been transmitted by another node, it will discard the packet. For the sender, if no neighbor nodes forward the packet in a contention window (T_{CW}), it will retransmit the packet. T_{CW} is set according to the transmission radius of the sender node. In the whole transmission, the described action of a single hop

repeats till the data is received by the gateway. The mechanism of next hop competition in CRB-RPL is shown in Algorithm 1.

Algorithm 1: RESPONSE-BASED ELECTION NEXT-HOP COMPETITION MECHANISM

```

i → node i
i receives the preamble and extracts information
if the sender has a higher rank than i then
    i receives the data
    waiting for  $\Delta t_i$ 
    i starts spectrum sensing
    if another node broadcasts the preamble in  $\Delta t_i$  then
        | turn into sleeping mode
    end
else
    if the same packet has been forwarded by other nodes then
        | i discards the packet
    end
    else
        if  $S_{idle}^j$  then
            | i broadcasts the preamble and data
        end
        else
            | i waits for available channels
        end
    end
end
end
else
    | i turns to sleep mode
end

```

In addition, receiver nodes distinguish whether the data is delay sensitive based on the data class information delivered by the preamble. For delay sensitive packets, the CRB-RPL class A is selected, wherein a *response-based* election mechanism is adopted in the next hop competition. For example (as shown in Fig. 3), three neighboring nodes of S (i.e., nodes A , B , and C) are eligible to forward the data towards gateway. After receiving the packet, each node lasts for a duration Δt before forwarding the packet, whose length is dependent on the rank difference between the sender node and the receiver node. Specifically, Δt for node i can be given by

$$\Delta t_i = \frac{\omega_4}{|Rank_s - Rank_i|} + \omega_5, \quad (9)$$

where $Rank_s$ and $Rank_i$ denote the ranks of the sender node and node i , respectively; ω_4 and ω_5 are constants.

As shown in (9), the node with a lower rank will have a shorter timer. Therefore, the low-rank node can perform spectrum sensing earlier, and have a higher chance to forward data.

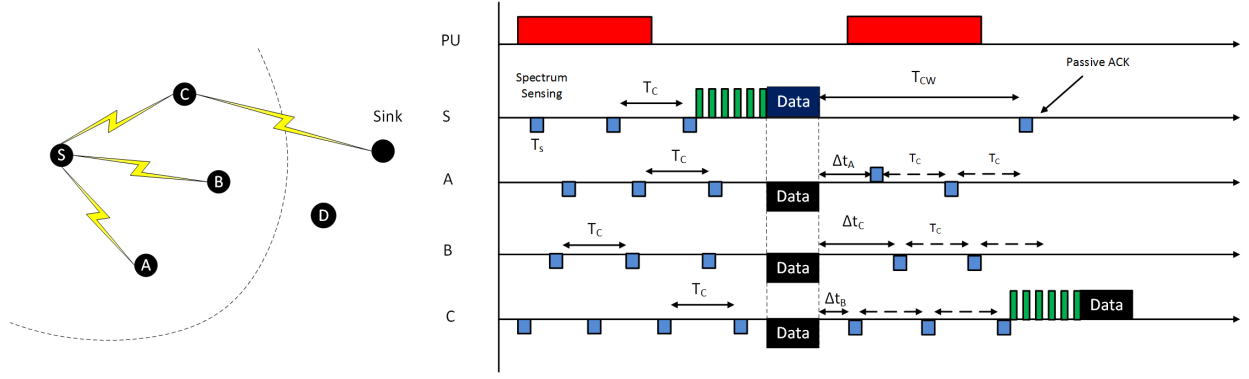


Fig. 3. Timeline of CRB-RPL routing with an illustrated scenario of sender and receiver nodes

If the packet is not delay sensitive, the energy efficiency of routing is taken into consideration and the class *B* is selected. For energy-efficient communications, both transmit power and other parts of energy consumption are taken into consideration [28], although it may change the fundamental tradeoff between energy efficiency and data rate [29].

In class *B*, the hop energy efficiency is the key consideration for the next hop competition. The hop energy efficiency is defined as follows.

Definition III.2. Hop Energy Efficiency: In multi-hop networks, the ratio of the hop distance of a single hop operation and its energy consumption is called the single hop operation's Hop Energy Efficiency (HEE).

HEE is used to quantify the energy efficiency of data transmission in ad-hoc networks. Since the class *B* focuses on energy efficiency of AMI networks in smart grid, the duration before each receiver (e.g., node *i*) performing spectrum sensing, i.e., Δt_i , is calculated on the HEE of the receiver node, which is given by

$$\Delta t_i = \frac{\omega_6}{\mathcal{E}} + \omega_7, \quad (10)$$

where \mathcal{E} denotes the HEE; ω_6 and ω_7 are constants.

According to definition, HEE can be computed as follows.

$$\mathcal{E} = \frac{D_{hop}}{E_{total}}, \quad (11)$$

where D_{hop} and E_{total} denote the hop distance between the sender and the receiver and the total energy consumption for forwarding the packet, respectively.

In this research, each receiver estimate its own HEE ignoring other receivers. The hop distance between the sender and the receiver can be represented by rank difference, which is given by

$$D_{hop} = |Rank_a - Rank_b|. \quad (12)$$

On the other hand, E_{total} are evaluated under realistic CR environments, where inaccuracy exists in spectrum sensing, which may lead transmission failures of both PU and secondary network users. In CRB-RPL, the failure probability of transmission on the j^{th} channel depends on the corruption in preamble or data frame, which is given by

$$P_{fail}^j = P_{sw}^j [1 - (1 - p)^{m+d}], \quad (13)$$

where m and d denote the size of micro-frame and data frame in bits, respectively, and p denotes the bit error probability.

On the receiver side, let r_m denotes the number of micro-frames in the preamble, given by $r_m = \lceil \frac{T_{pr}}{T_m} \rceil$. The expressions for energy drained in a single successful and failed transmission on the j^{th} channel are given by

$$E_{R_{succ}}^j = E_{ss}^j + P_{sw}^j \{ (1 - p)^m (\tau + T_s) + (1 - p)^d (\tau + T_d) \} \mathcal{P}_r, \quad (14)$$

$$E_{R_{fail}}^j = E_{ss}^j + P_{sw}^j \{ (\tau + T_s) + (1 - (1 - p)^d) (\tau + T_d) \} \mathcal{P}_r, \quad (15)$$

where \mathcal{P}_r denotes the power drained in the receive mode, E_{ss}^j denotes the energy consumption for spectrum sensing and τ denote the transition time from sleep mode to active mode.

In case of a failed transmission, the sender node will retransmit the data. The number of retransmission is computed based on *Expected Transmission Count* (ETX) [30]. The ETX of a link from the sender to the receiver is given by $\mathbb{E}_{sr} = 1/\rho_{sr}$, where ρ_{sr} is the probability of the receiver node r receiving a transmission from the node sender s . The ETX between two nodes can be measured in advance, and updated continuously, when the link starts to carry data traffic. Therefore, the energy consumption for a node to receive a packet successfully is given by

$$E_R^j = (\mathbb{E}_{sr} - 1) E_{N_{fail}}^j + E_{R_{succ}}^j + \chi_{ss}^j E_{ss}^j, \quad (16)$$

where E_{ss} denotes the energy drained in spectrum sensing, and χ_{ss}^j denotes the expected number of sensing events for transmitting over the channel j .

The energy drained during spectrum sensing is given by

$$E_{ss}^j = (\tau + T_s) \mathcal{P}_s, \quad (17)$$

where \mathcal{P}_s denotes the power required for spectrum sensing operation, and τ denotes the transition time from sleep mode to active mode.

The expected number of sensing events for transmitting over the channel is given by

$$\chi_{ss}^j = \sum_{i=0}^{\infty} i \cdot (1 - P_{sw}^j)^i P_{sw}^j = \frac{1 - P_{sw}^j}{P_{sw}^j}. \quad (18)$$

On the transmitter side, the energy consumption can be evaluated based on Shannon's theorem. It is assumed that the minimum of requested rate is R_d . The capacity of channel j satisfy the following condition

$$C^j = W_i \log_2 (1 + SNR^j) \geq R_d, \quad (19)$$

As a result, the minimum required transmit power over the channel j is given by

$$\mathcal{P}_{min}^j = \frac{\left(2^{\frac{R_d}{W_i}} - 1\right) \delta^2}{|(h^j)^2|}, \quad (20)$$

where h_i is channel coefficient, given by

$$h^j = F^j \sqrt{1/L^j}, \quad (21)$$

where F^j is the fading coefficient of the channel where L^j is the path loss and computed using Okumura model [31].

Therefore, the energy consumption for transmission is given by

$$E_T^j = \mathcal{P}_{min}^j \cdot T_p, \quad (22)$$

where T_p accounts for the duration of transmitting the packet.

The total energy consumption for a node to act as the next hop is given by

$$E_{total} = E_R^j + E_{pp} + E_T^j. \quad (23)$$

IV. ANALYTICAL MODELING

A. Delay

In case of a failed transmission, the sender node will retransmit the data. Therefore, it is necessary to analyze the model of retransmission for CRB-RPL. We assume that the total number of transmissions until a success transmission can be represented by a random variable. The probability of a successful transmission after v failures can be given by

$$P_v = (1 - (P_{fail}^j)^N) (P_{fail}^j)^{N \cdot v}. \quad (24)$$

The average number of retransmissions until success can be given by (25), where V_{max} represents the maximum number of retransmissions.

$$\chi = \sum_{v=0}^{V_{max}} v \cdot P_v = \sum_{v=0}^{V_{max}} v \cdot (1 - (P_{fail}^j)^N) (P_{fail}^j)^{N \cdot v}. \quad (25)$$

Using the retransmission model, the end-to-end delay for data transmission in CRB-RPL routing can be calculated as follows.

$$D = \sum_{h=1}^H \chi^h \cdot (T_{pr} + T_d + T_{CW}) + \Delta t_i^h + \chi_{ss}^h \cdot T_s + (\chi_{ss}^h - 1) \cdot T_C, \quad (26)$$

where H denotes the number of hops, χ^h denotes the number of retransmission over h^{th} hop, Δt_i^h denotes the duration before spectrum sensing for forwarding over h^{th} hop, and χ_{ss}^h denotes the number of spectrum sensing events over h^{th} hop.

B. Energy Consumption

On the transmitter side, the expressions for energy drained in a single successful and failed transmission on the j^{th} channel are given by

$$E_{-T_{succ}}^j = \chi_{ss}^j E_{ss}^j + P_{sw}^j \left\{ (1-p)^m \left[\frac{T_{pr}}{T_m} \right] T_m + (1-p)^d T_d \right\} \mathcal{P}_t, \quad (27)$$

$$E_{-T_{fail}}^j = \chi_{ss}^j E_{ss}^j + P_{sw}^j \left\{ \left[\frac{T_{pr}}{T_m} \right] T_m + (1 - (1-p)^d) T_d \right\} \mathcal{P}_t, \quad (28)$$

where \mathcal{P}_t denotes the power drained in the transmit mode, T_d is the duration of data frame, T_{pr} denotes the preamble duration, T_m is the time for a single micro-frame transmission, and τ is the transition time from sleep mode to active mode.

On the receiver side, the nodes can detect the preamble transmission by using spectrum sensing, when the PU is not active. The expressions for energy drained in a single successful and failed transmission over channel j are given by (14) and (15), respectively. However, for a single hop, there are N eligible receivers for forwarding the data packet. Therefore, the energy consumed in a single successful transmission in all possible cases where i nodes ($i \leq N$) receive the packet successfully is given by

$$E_{-R_{N_succ}}^j = \frac{\sum_{i=1}^N \binom{N}{i} \left[i E_{-R_{succ}}^j + (N-i) E_{-R_{fail}}^j \right]}{\sum_{i=1}^N \binom{N}{i}}. \quad (29)$$

The energy consumed in a single transmission when all the receiver nodes fail to receive the packet without error is given by:

$$E_{-R_{N_fail}}^j = N \cdot E_{-R_{fail}}^j. \quad (30)$$

Therefore, the total energy consumption for data packet transmission is given by

$$E_{total_A} = \sum_{h=1}^H \chi^h (E_{-T_{fail}}^h + E_{-R_{N_fail}}^h) + E_{-T_{succ}}^h + E_{-R_{N_succ}}^h + \chi_{ss}^h E_{ss}^h, \quad (31)$$

where $E_{-T_{fail}}^h$ denotes the energy consumption for transmitting in failed transmission over h hop, $E_{-R_{N_fail}}^h$ denotes the total energy consumption during receiving in failed transmissions over h^{th} hop, $E_{-T_{succ}}^h$ denotes the energy consumption for transmitting in successful transmission over h hop, $E_{-R_{N_succ}}^h$ denotes the total energy consumption during receiving in successful transmissions over h^{th} hop, and E_{ss}^h denotes the energy consumption for spectrum sensing over h^{th} hop.

C. Coordination Overhead

Due to the receiver-based nature, no acknowledgement (ACK) frames are used in CRB-RPL. The preamble transmitted by a receiver for next-hop transmission can be regarded as the passive ACK. However, in practice, there is an associated probability of erroneous forwarding of the same frame by multiple nodes due to failure transmission of the preamble. Hence, we consider the *coordination overhead*, which is the probability of a node in the forwarder set transmitting a frame when any other node has already forwarded it. The CO of a single hop (e.g., the h^{th} hop) is given by

$$CO_h = \{P_{sw}^j [1 - (1 - p)^m]\}^{\lfloor \frac{T_{pr}}{T_m} \rfloor \cdot N}. \quad (32)$$

Therefore, the coordination overhead for the route can be given by

$$CO = \prod_{h=1}^H (1 + CO_h). \quad (33)$$

D. Reliability

In this paper, *Packet Delivery Ratio* (PDR) is adopted for reliability performance evaluation of CRB-RPL, which can be calculated by the fraction of the received packet number to the total packet number. Analytically, the end-to-end PDR for CRB-RPL routing is given by

$$R = \prod_{h=1}^H \left(1 - (P_{fail}^{C_h})^{N_h(\chi^h + 1)}\right), \quad (34)$$

where C_h and N_h denote the selected channel over h^{th} hop, and the number of receivers over h^{th} hop, respectively.

V. PERFORMANCE EVALUATION

In this section, we evaluate the performance of CRB-RPL under different scenarios. We implement CRB-RPL with the topology as shown in Fig. 4. We consider a square region of sides 1200 meters that is occupied by 16 PU transmitters. The secondary users are assumed to be Poisson distributed in the whole region with a mean density. We consider a frequency selective Rayleigh fading channel between any two nodes, where the channel gain accounts for small scale Rayleigh fading, large scale path loss and shadowing. We also compare our protocol with CORPL and RPL in the same simulation configuration. Other simulation parameters are given in TABLE I.

Firstly, the number of hops of CRB-RPL is evaluated. As shown in Fig. 5, the hop count decreases as the CR network density increases. Since, the probability of a node associating with a lower ranked node increases, a higher density results in faster dissemination of network information owing to more nodes in the coverage range. CRB-RPL is inherently receiver-based, and nodes with lower rank have larger probability to forward packets. Especially, in CRB-RPL class A, the rank is an important factor for the next-hop completion, so that it needs less hops to achieve the packet transmission from the sender to the gateway.

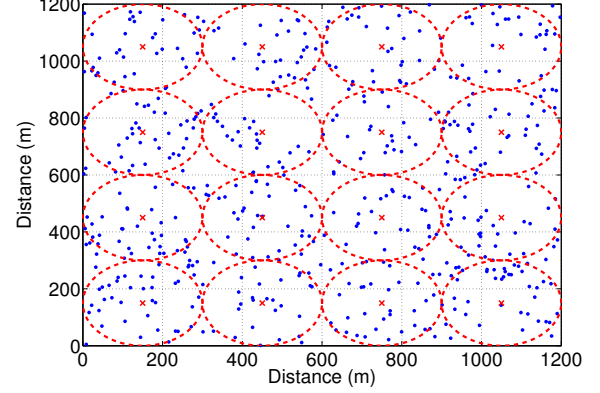


Fig. 4. Simulated network topology. The circles represent the coverage area of PU transmitters. The density is 3×10^{-4}

TABLE I
SIMULATION CONFIGURATION PARAMETERS

Parameter	Value
Path loss model	$128.1 + 37.6 \log_{10}(r)$, r in km
Standard deviation of shadowing	8 dB
Detection probability threshold (P_d)	0.9
Probability of false alarm (P_f)	0.1
Channel bandwidth	200KHz
PU received SNR (γ)	-15dB
Busy state parameter of PU (μ_{ON})	2
Idle state parameter of PU (μ_{OFF})	3
Size of DIO message including options	28 bytes
Power drained in transmit mode (P_t)	66.16 mW
Power drained in receive mode (P_r)	70.69 mW
Power drained in spectrum sensing (P_s)	65.83 mW
Checking interval (T_C)	144 ms
Preamble length (T_{pr})	144 ms
Transmission time of a data packet (T_d)	4 ms
Transmission time of one micro-frame (T_m)	40 μ s
Time from sleep mode to active mode (τ)	88.4 μ s

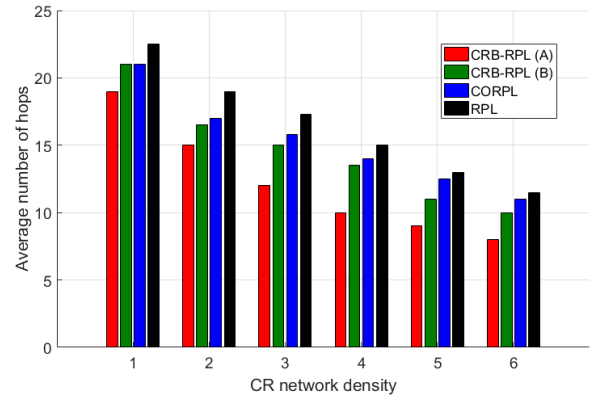


Fig. 5. Average number of hops towards gateway for different node densities.

Next, the end-to-end delay performance with different *Link Success Probability* (LSP) is evaluated. As shown in Fig. 6, the end-to-end delay decreases as LSP and network density increase. This is because retransmissions is less with larger probability of successful transmission. Moreover, higher network density can reduce the number of hops (as shown in Fig. 5). CRB-RPL class A, which is for delay sensitive packets, outperforms CORPL and RPL in end-to-end delay performance obviously. This is because delay is dependent on the number of retransmissions, CRB-RPL outperforms the two sender-based protocol in terms of delay performance due to fewer retransmissions.

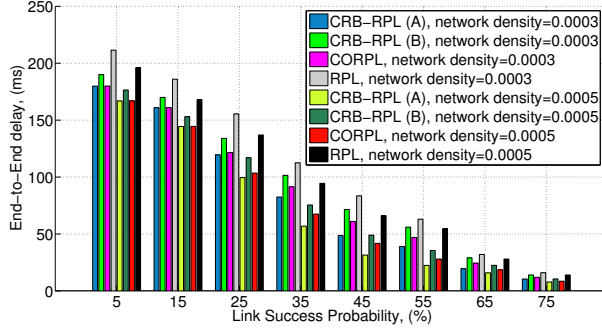


Fig. 6. End-to-end delay against Link Success Probability (10, 000 packets are transmitted, and node density = 3×10^{-4} nodes per unit).

We also evaluate the delay performance against different transmission distance. Fig. 7 shows the plot of the average end-to-end delay of inward traffic against the distance between the source to gateway. This figure indicates that the average end-to-end delay of class A is within 1s, which is better than those of RPL and CORPL. The performance of class B is near to that of CORPL but better than that of RPL. We conclude that CRB-RPL is not very sensitive to transmission distances.

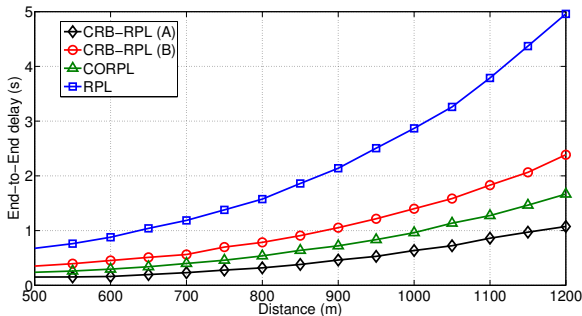


Fig. 7. End-to-end delay against distance (10, 000 packets are transmitted, and node density = 3×10^{-4} nodes per unit).

Fig. 8 depicts the single hop energy consumption performance against the bit error rate (BER). In channels with rather low BER, both classes A and B outperform other protocols in terms of energy consumption. This is mainly because, energy consumption of nodes involved in the retransmission is low. In very poor channel conditions, class A consumes more energy than CORPL and the energy consumption increases with the number of the receivers, while class B has a good

performance. The energy consumption reaches a saturation point when maximum number of retransmissions is reached. More energy is spent in reception process as a result increases the overall energy consumption. It is also noted that class B still has a accepted performance.

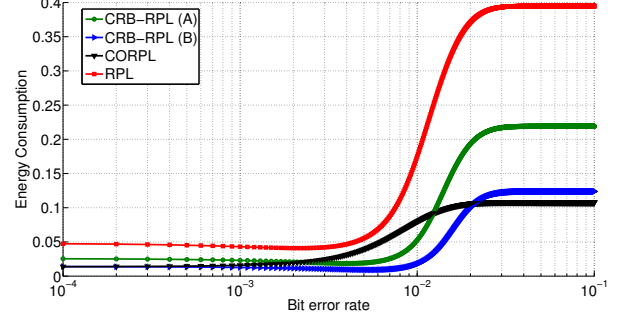


Fig. 8. Average energy consumption for a single hop operation against bit error rate (10, 000 packets are transmitted, and node density = 3×10^{-4} nodes per unit).

We also evaluate the average energy consumption of single hop against node density in Fig. 9. CRB-RPL outperforms CORPL and RPL when the node density is low, especially, the energy consumption of class A is around half of that of CORPL and a third of that of RPL. The energy consumption increases as the node density increases. In high node density environment, the benefit of CRB-RPL is reduced and performances of all the protocols get close. This is because the number of receivers increases as the node density increases.

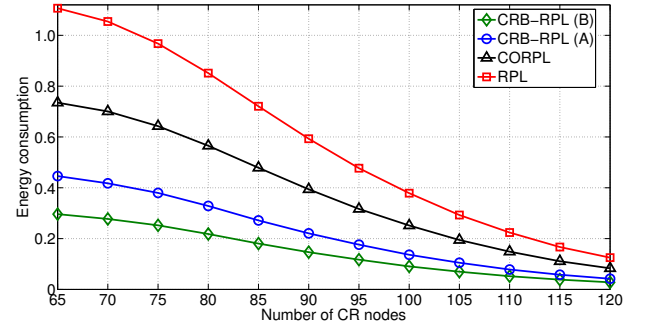


Fig. 9. Average energy consumption (Joule) for a single hop operation against node density (10, 000 packets are transmitted).

In Fig. 10, we evaluate the *Coordination Overhead* (CO) of the CRB-RPL, which is defined as the ratio of the duplicate packet number to the total packet number received at the gateway. The CO of CRB-RPL decreases as the LSP increases due to the fact that the probability of nodes not capturing the preamble decreases. If a receiver fails to capture the preamble transmitted by another receiver, it may forward the same packet, which results in duplicate packet forwarding. In CRB-RPL, the preamble consists of several micro-frames, and each micro-frame carries all the auxiliary information for the packet transmission. Capture of any micro-frame will avoid the duplicate packet forwarding. Therefore, the CO performance of CRB-RPL outperforms those of CORPL and RPL.

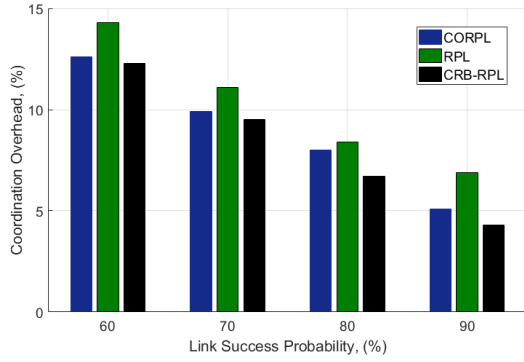


Fig. 10. Coordination overhead for CRB-RPL against link success probability (10,000 packets are transmitted, and node density = 3×10^{-4} nodes per unit).

At last, we discuss the reliability performance in terms of *Packet Delivery Ratio* (PDR), which is defined as the ratio of number of packets successfully received to the total number of packets sent. We generate 10,000 packets from different nodes and calculate the average PDR for different scenarios as shown in Fig. 11. We note that CRB-RPL provides larger PDR compared to those of RPL and CORPL under both good and poor channel conditions due to its receiver-based nature. For example, PDR of CRB-RPL is more than 80% as the LSP is at 75%.

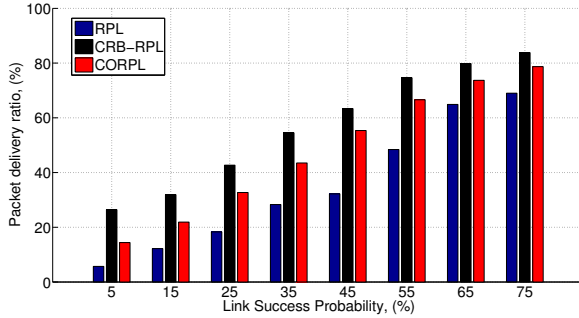


Fig. 11. Packet delivery ratio against link success probability (10,000 packets are transmitted, and node density = 3×10^{-4} nodes per unit).

VI. CONCLUSIONS

This paper has considered two main challenges in CR-enabled AMI networks, the realtime and energy efficiency requirements, in order to realize the vision of smart grids. Therefore, we have proposed a new routing protocol, i.e., CRB-RPL, which is an enhanced RPL-based routing protocol for CR-enabled AMI networks. Different from traditional sender-based routing protocols, CRB-RPL is receiver-based, which fully exploits the broadcast nature of wireless communications to reduce retransmissions and improve routing efficiency. Furthermore, two classes of routing protocols are proposed for different smart grid application requirements: class A for delay-sensitive applications, whereas class B for applications with energy efficiency requirements. In addition, CRB-RPL has incorporated the CTQ concept for rank computing, which not only ensures QoS but also fulfills the utility requirement of

the secondary network. Analytical and simulation results have shown that CRB-RPL can supply realtime and energy-efficient routing in CR-enabled AMI networks, while reducing harmful interference to PUs. Hence, the proposed routing protocol, i.e., CRB-RPL, provides a viable solution for practical AMI networks. The future work will focus on the analysis of CRB-RPL over multiple networks.

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